Far-Infrared and Submillimeter Emission of the Interstellar Medium.
Editors : C. Kramer, R. Simon et al.
EAS Publications Series, 2008

THE FAR-IR VIEW OF SGR B2 AND ORION KL: TEMPLATE STAR-FORMING REGIONS

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Abstract. We summarize the main highlights from *ISO* observations towards Sgr B2 and Orion KL in the far–IR domain ($\sim$43 to 197 μm). Both Star–Forming Regions are among the best sources to construct a *template* for more distant and unresolved regions (e.g., extragalactic). We stress some peculiarities in the interpretation (excitation and radiative transfer) of far–IR spectral lines and dust continuum emission.

1 Introduction

Sgr B2 ($d \simeq 8.5$ kpc) and Orion KL ($d \simeq 450$ pc) can be considered to be the two most remarkable giant molecular clouds for Astrochemistry and Star-Forming Region (SFR) studies. They are also very appropriate sources to construct a *template* for more distant (e.g., fainter) and unresolved regions (e.g., extragalactic).

Sgr B2, represents the most active burst of high–mass star formation in the Galactic Center region (Lis & Goldsmith 1989). Its geometrical properties (clumped extended envelope, centrally condensed hot cores and H II regions), its physical conditions (widespread warm gas, enhanced turbulence and UV– and X–ray radiation fields) as well as its chemical complexity (extended emission of refractory and organic species) mimic a miniature "Galactic Center". Therefore, it provides the closest *guide* for studies of starbursts vs. active galactic nuclei.

Orion is the nearest and best studied high–mass SFR (Genzel & Stutzki 1989). Due to its proximity, high spectral and angular resolution observations allow us to separate the very different physical components associated with high–mass SFRs (hot cores, outflows, shocks, PDR-like interfaces and ambient gas). In particular, Orion has been traditionally used to *test* our understanding of the physics and chemistry in hot cores (e.g., IRc2) and extended shocked regions (e.g., Peaks 1/2).

The cores of both SFRs are the most prolific sites of molecular line emission/absorption in the Galaxy (in terms of density and intensity/depth of lines).

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DOI: (will be inserted later)

Due to the large column density of warm material (Sgr B2) or due to its proximity (Orion), both complexes are among the brightest far–IR sources in the entire sky. For these reasons, Sgr B2 and Orion KL were fully surveyed between $\sim$43 and 197 μm at the maximum spectral resolution provided by the ISO/LWS Fabry–Pérot ($\lambda/\Delta\lambda \sim$10,000 or $\sim$30 km s^{-1}). These data cover an extremely important region of the electromagnetic spectrum that can not be accessed from the ground. The resulting spectra remain unique examples of the diagnostic power of this domain, and archetypes of what future far–IR space missions will routinely observe. In this constribution we review the main highlights of ISO data and we stress some peculiarities in the interpretation of far–IR line and continuum emission.

2 The far-IR spectrum of a high–mass SFR

The far–IR spectrum of Sgr B2 (Goicoechea et al. 2004; Polehampton et al. 2007 and references therein) contains: (*i*) The peak of the thermal emission from dust (a blackbody at 30 K roughly peaks at 100 μm); (*ii*) Atomic fine structure lines that are major coolants of the warm gas, and excellent discriminants of the PDR, H II and shock emission (O I, O III, C II, N II, N III); (*iii*) Rotational lines from key light hydrides (H_2O, OH, H_3O^+, CH_2, CH, NH_3, NH_2, NH, HF, HD, H_2D^+) and ro-vibrational lines from abundant nonpolar molecules (C_3). These species provide unique information on the prevailing physical conditions and on the basic O, C, N and D chemistry. Most of the molecular lines appear in absorption whereas atomic and ionic lines appear in emission (except for absorption in the [O I]63 and [C II]158 μm lines). In particular, [O I]63 and [C II]158 μm velocity resolved absorption line profiles provide clues regarding several peculiarities observed in some extragalactic spectra at lower resolution (e.g., the C II/far-IR deficit). The main gas component traced by far–IR observations is the warm, low density envelope of Sgr B2 (T$_k \simeq$300-500 K; n(H$_2$)$<10^4$ cm^{-2}). Given the low densities in this component, no high–J CO line was detected at ISO's sensitivity. This situation may apply to other *warm* regions observed in the far–IR. The warm, low–density gas is particularly difficult to trace in the millimeter domain where one usually observes molecular emission lines from collisionally excited gas (i.e., from the denser star forming cores). Finally, because of its location in the Galactic Center, all ground–state lines towards Sgr B2 show a broad absorption profile ($\Delta v \simeq$200 km s^{-1}) due to foreground absorption produced by the spiral arm clouds in the line of sight.

On the other hand, the far–IR spectrum of Orion KL (Lerate et al. 2006 and references therein) is dominated by emission lines from molecular (H_2O, OH, NH_3, high–J CO) and atomic species. Interestingly enough, H_2O and OH line profiles show a complex behavior (when observed at high spectral resolution) evolving from pure absorption, P Cygni type, to pure emission, depending on the transition wavelength, E_{up} and line opacity. These lines arise from Orion outflow(s) and associated shocked regions. Without resolving these profiles, low resolution spectra of similar regions may lead to a misinterpretation of the prevailing dynamics and physical conditions. Given the high densities and temperatures of Orion's shocked gas, CO emission up to J=39 has been detected (E$_{up}/k \simeq$4,000 K).

2.1 Far-IR line and continuum interpretation

Both SFRs show a strong far-IR continuum due to thermal emission of dust grains. In the case of Sgr B2 ($T_d \simeq 30$ K), the continuum emission towards the main star forming cores (M and N) is optically thick in most of the far–IR domain ($\tau_d > 1$). This particularity greatly influences the excitation of molecular species and also produces a *screen effect*, i.e., **continuum** and **line** observations are mostly sensitive the **outer layers of the cloud** (its envelope). Since different cloud depths are traced at different wavelengths, a correct interpretation of far–IR observations requires a careful treatment of the dust radiative transfer problem.

Molecular and atomic lines can appear in absorption towards a strong far–IR background (e.g., Sgr B2). This means that lines arise in regions were excitation temperatures (T_{ex}) are lower than the brightness temperature of the underlying continuum ($\simeq T_d$). Therefore, even if collisional excitation plays a role, far-IR dust photons decisively affect the level population, and thus T_{ex}. In particular, a strong far-IR radiation field can efficiently pump high energy levels even if $T_k << E_{up}/k$ (e.g., H_2O lines with E_{up}/k up to $\sim$2,000 K have been detected towards Orion KL where we estimate $T_k \simeq 100$ K). In consequence, level populations can be primarily determined by the thermal emission of dust and not by inelastic collisions with other species. Since line photons cool the gas when energy is transfered from kinetic motions into radiation that escapes the cloud, photons emitted from such radiatively pumped transitions do not contribute to the *gas cooling*. Instead, they may contribute to the *gas heating* through collisional de-excitation. Furthermore, given the high critical densities of far–IR molecular transitions, *collisional* thermalization (LTE) hardly occurs at the typical densities of molecular clouds. Transitions can be however very close to *radiative* thermalization ($T_{ex} \simeq T_d$). These are the main differences with the radiative transport at lower frequencies (e.g., the mm domain), where one can usually neglect the effect of dust emission/absorption.

In summary, line radiative transfer and level excitation of the species dominating the far–IR spectra of Sgr B2 and Orion are characterized by: (*i*) Broad range of radiative and collisional rate coefficients (e.g, with closely spaced transitions in wavelength but with line strengths and Einstein coefficients that vary by orders of magnitude). (*ii*) Both collisional excitation (with H_2, He and even H and e^- in regions like PDRs where the electron abundance is large and the molecular fraction is low), and radiative excitation by dust photons play a role. (*iii*) Gas and dust coupled radiative transfer. Very large line and continuum opacities are possible. The former point ($\tau_{line} >> 1$) often leads to line–trapping and significant scattering in the lowest-energy transitions produced by foreground low density halos. The later point ($\tau_d > 1$) makes that **even** optically thin lines do not trace the full cloud line–of–sight because the line profile is formed in the outermost cloud layers not veiled by the dust opacity (e.g., *hidden* hot core emission). Therefore, molecular excitation is generally a highly nonlocal, non–LTE problem, where standard analysis tools (rotation diagrams or LVG) are often non applicable. Additional complications may arise in the presence of velocity fields (e.g., P Cygni profiles from Orion's outflows) or overlapping transitions (e.g. OH hyperfine components).

Depending on each situation, a minimum treatment of some of these effects is required to correctly extract the physical conditions and chemical abundances.

2.2 Open problems: oxygen chemistry and gas heating

Many unsolved questions remain regarding the origin of the oxygen chemistry (e.g., main water formation routes in Orion) and the dominant heating mechanisms (e.g., Sgr B2 envelope). The relatively large (beam–averaged) water and OH abundances inferred towards Orion KL ($\chi(H_2O) \simeq 2\times10^{-5}$ and $\chi(OH) \simeq 10^{-6}$) but moderate temperatures ($T_k \simeq 100$ K) either suggests that (*i*) H_2O could have been formed in the shocked gas by neutral–neutral reactions with activation barriers if the gas was previously heated to $\geq$500 K, and/or (*ii*) H_2O formation in Orion outflow(s) is dominated by *in situ* evaporation of grain water–ice mantles, an/or (*iii*) H_2O is formed in the inner hot core regions and then is swept up by the outflow (Cernicharo et al. 2006a; Goicoechea et al. 2006).

Similar OH and H_2O abundances have been inferred towards Sgr B2's envelope (Goicoechea & Cernicharo 2002; Cernicharo et al. 2006b) where beam–averaged temperatures are higher ($T_k \simeq$300-500 K). Penetration of UV radiation from ionizing stars is thought to play a role in the cloud physics and chemistry. Still, it is not clear wether radiative (e.g. photoelectric) or mechanical (e.g., shocks) heating mechanisms are the origin of the high temperatures. The improved sensitivity of future space missions will allow key spectral diagnostics to be *mapped* over very large areas. In addition, abundant molecular species such as H_2O and OH will dominate the far-IR spectra of extragalactic nuclei, providing excellent diagnostic tools of the warm gas (see Goicoechea et al. 2005 for OH detections in NGC 253 and NGC 1068). Sgr B2 and Orion KL will, however, remain as key templates to constrain the chemical content and spatial segregation in SFRs, and to study the physical mechanisms that play a role in the cloud dynamics and chemistry.

I warmly thank J. Cernicharo, E. Polehampton, F. Daniel and M.R. Lerate for fruitful discussions on Sgr B2, Orion, radiative transfer and ISO observations. F. Daniel is also acknowledged for commenting a draft version of the manuscript.

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